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ABSTRACT

A sensitive measurement by rocket borne detectors of the x-ray flux from Cas A has revealed a steep continuum and a broad spectral feature in the region where line radiation from iron nuclei would be expected. The flux in this feature is .0122 $\pm$ .0017 photons $cm^{-2}s^{-1}$; the total energy flux from 2 to 10 keV is 1.02×10^{-9} ergs $cm^{-2}s^{-1}$. The presence of broad iron lines is consistent with a model in which $\sim$ 13 MeV/nucleon iron nuclei charge exchange with surrounding interstellar oxygen and other heavy atoms. The model suggests that a substantial fraction of the energy from the outburst has gone into low energy cosmic rays which produce the observed HII region surrounding the remnant.

I. INTRODUCTION

Cas A is believed to be the youngest known supernova remnant in the galaxy resulting from an explosion that took place around 1667 A.D., about 2.8 kpc away (Van Den Bergh & Dodd 1970). Optical studies of the remnant reveal a rapidly expanding nebula surrounded by a faint HII region which extends out to 5.7 pc from the site of the explosion. The remnant is a strong source of nonthermal radio emission being by far the brightest radio source in the sky.

Byram, Chubb and Friedman (1966) first detected Cas A in the X-ray band in a 1965 rocket survey. Gorenstein, Kellogg and Gursky (1970) produced the first spectrum for this source in the band 2 to 10 keV. The UHURU catalogue of X-ray sources (Giacconi et al. 1972) lists Cas A as a steady emitter and one of the relatively few sources with which a definite optical identification has been made. The lack of temporal variations (Holt et al. 1973), as well as the nature of the optical and radio emissions strongly implies that the X-ray source is an extended object, much as the source in the Crab Nebula and unlike such thermal sources as Sco X-1 and Cyg X-2, or the eclipsing binaries Her X-1 and Cen X-3.

In this paper we shall present new spectral information pertaining to the X-ray flux from Cas A, obtained from a rocket borne experiment launched from White Sands, New Mexico at 0900 UT on 19 May 1972.

II. THE EXPERIMENT

We scheduled most of the available time in the rocket flight to conduct a sensitive study of Cas A and of the nearby Tycho remnant.

Results from a temporal analysis of the data from both sources have been reported elsewhere (Holt et al. 1973). The data we are presenting here were obtained with a xenon-filled, multi-anode, multi-layer proportional counter, equipped with a .001" kapton window and a 3-degree circular Cu collimator. The total open area is 711 cm^2. The exposure to Cas A lasted 61.4 seconds. Star field pictures showed that the detector was pointed to within 0.1 degrees of the source throughout the exposure, during which time the counting rate averaged 93.4 s^{-1}. The average background rate was measured at 16.8 s^{-1}. An onboard Fe^{55} source provided calibration data before the doors to the experiment opened, as well as after they closed at the end of the flight.

III. ANALYSIS

We will present the data in a representation that, we believe, best allows for comparisons with other observations. We have computed an incident spectrum S(E) at energy E as follows:

$$S(E) = \frac{N_{obs}(E)}{\epsilon(E)} \qquad (1)$$

where N_{obs} are the net observed counts from the source, and ϵ is an effective efficiency defined as

$$\epsilon(E) = \frac{N_{calc}(E)}{S'(E)} = \frac{C\int_0^\infty R(E,E')S'(E')dE'}{S'(E)} \qquad (2)$$

where R(E,E') is the detector response function as determined from source calibration, which relates the apparent energy to the incident true energy, S'(E) is a first approximation to the source spectrum, and C is a normalization constant. A usual procedure for arriving at an approximate expression for S(E) has been to use equation 2 for computing $N_{calc}(E)$, which is then compared with $N_{obs}(E)$ using the χ^2 method. This may require a prohibitive number of trial functions when S(E) involves many parameters. In this paper we proceed to obtain better approximations for S(E) using the above integral equation, starting with S'(E) = constant. This procedure converges rapidly, resulting in a near final representation for S(E) even after only one iteration. It is, of course, obvious that any sharp features of the incident spectrum, such as lines, will be smoothed over by an amount commensurate with the energy resolution of the instrument.

IV. RESULTS

In Figure 1 we show the incident spectrum for Cas A inferred from an analysis as described above. No statistically significant net flux was detected above about 15 keV. The spectrum appears to be made up of more than just a single component. If we exclude the region 5 to 10 keV, a good fit is obtained using a single power law with some absorption at the lower energies. The index to the best fit number spectrum is 4.5; the absorption implies interstellar matter in the line of sight of 1.4×10^{22} hydrogen atoms cm^{-2}, based upon the cross sections given by Brown and Gould (1970). We find no major segment of the data that can be similarly fitted with a simple thermal continuum. Assuming that a power law with an additional component in the range 5 to 10 keV does adequately represent the incident spectrum, we have subtracted from the data the appropriate power law and we have plotted the residual flux in Figure 2. It is particularly significant that the broad residual is centered near 7 keV, a region where the dominant K-shell transitions from Fe^{+25} and Fe^{+24} would be expected. However, the feature in the data is too broad to be attributed to collisionally stripped ambient iron. Assuming that the residual in Figure 2 is due to iron lines, the observed broadening is not likely to have resulted from electron scattering of the radiation in a compact thermal source, but is probably due to electron cascades to the ground state in fast iron nuclei following charge exchange with neutral matter (cf. Silk and Steigman 1969). We note that the magnitude of the emission feature in relation to the continuum is prohibitively high (cf. Felten, Rees and Adams 1972) for a thermal spectrum. Furthermore, we reiterate that we could not fit any segment of the observed spectrum with a thermal continuum, especially one with the high temperature needed to account for the presence of iron lines. Finally, we note that much of the previous evidence supports an extended source model for Cas A.

If the interstellar region surrounding the remnant is permeated with low energy cosmic rays (i.e. a few MeV/nucleon) ejected by the supernova (cf. Ramaty et al. 1971) we can expect high Z nuclei to slowly lose their effective charge through accumulation of atomic electrons via charge exchange with ambient neutral atoms. A substantial number of transitions to the ground state from higher excited states will result in 2p-1s transitions at $\sim$ 7.0 keV and 6.7 keV from H-type and He-type Fe respectively. These lines will subsequently be Doppler shifted to a degree depending on the velocity of the emitting ion. The final distribution will be a composite of all contributing lines. Although the contribution from lower Z elements could be comparable, the main effect will occur below about 2 keV where the total intensity is more than an order of magnitude greater than at 7 keV.

To test this model, we fitted our data with the spectrum

$$\frac{dN}{dE} = C_1[E^{-\alpha} + C_2 \frac{1}{\sqrt{2\pi}\sigma} e^{-(E-6.9)^2/2\sigma^2}] e^{-x\sigma_g} \quad , \qquad (3)$$

where $x = 1.4 \times 10^{22}$ hydrogen atoms cm^{-2} and σ_g is the effective absorption coefficient for the interstellar medium (Brown and Gould 1970). The best fit gives $\chi^2 = 17$ for 12 degrees of freedom, and was obtained with $\alpha = 4.5 \pm .07$; $\sigma = 1.23 \pm .09$ keV; $C_1 = 8.49$ photons $cm^{-2}s^{-1}keV^{-1}$; $C_2 = .00147$. The errors shown are those that cause χ^2 to increase by 1 when a corresponding parameter alone is allowed to change. If we set

$$\sigma^2 = \sigma^2_{intrinsic} + \sigma^2_{instrument} \qquad (4)$$

and substitute the measured detector resolution $\sigma_{instrument} = .54$ keV, we obtain $\sigma_{intrinsic} = 1.1$ keV. If we now assume that the 6.7 and 7.0 keV lines contribute equally, we conclude that single lines at the source are broadened by about 33%. The corresponding particle energy is 13 MeV/nucleon.

The residue in Figure 2 amounts to a flux of $.0122 \pm .0017$ photons $cm^{-2}s^{-1}$. In the range 2 to 10 keV, we obtain a number flux of .223 photons $cm^{-2}s^{-1}$ and an energy flux of 1.02×10^{-9} ergs $cm^{-2}s^{-1}$.

V. DISCUSSION

Although Gorenstein, Kellogg and Gursky (1970) fitted the Cas A spectrum with a single power law they noted that the emission could be more complex since they did not obtain an acceptable fit. An examination of their published data points indicates that the present model could provide a better fit. The amount of interstellar absorption inferred from their data is in good agreement with that given in this paper, both being consistent with 21-cm absorption measurements (cf. Davies and Shuter 1963). The UHURU catalogue gives an energy flux for Cas A of 9.1×10^{-10} ergs $cm^{-2}s^{-1}$ in the range 2 to 10 keV, in excellent agreement with our result.

A recent supernova remnant is a likely place to look for effects attributable to fast charged particles. If an appreciable fraction of the energy in the outburst goes into such particles, their effects may include the ionization of the surrounding region and the radiation which results from interactions with ambient matter. In $\sim$ 300 years, the age of the Cas A remnant, 13 MeV/nucleon nuclei will traverse in straight line trajectories a distance of 15 pc, but the actual rectilinear distance away from the explosion may be smaller because of magnetic fields. Peinbert and Van Den Bergh (1971) discuss an HII region which surrounds the Cas A remnant and which extends out to 5.7 pc. From the emission measure they estimate an r.m.s. electron density in the region of 15 cm^{-3}. We shall explore the possibility of a closer tie between this observation and our charge exchange model.

Nikolaev (1965) gives the following approximate expression for the cross section for charge exchange as a function of the velocity v of a highly stripped nucleus of charge Z incident upon a medium of atomic number Z_{med}:

$$\sigma_n = \frac{2^{18}}{5}\pi a_o^2 Z^2 \left(\frac{Z}{n}\right)^3 Z^5_{med} \left(\frac{V}{Vo}\right)^8 \left[\left(\frac{V}{Vo}\right)^4 + 2\left(\frac{V}{Vo}\right)^2 \left(Z^2_{med} + \frac{Z^2}{n^2}\right) + \left(Z^2_{med} - \frac{Z^2}{n^2}\right)^2 \right]^{-5} \quad (5)$$

where $a_o = .528 \times 10^{-8}$ cm, the radius of the first Bohr orbit, and $v_o = 2.19 \times 10^8$ cm s^{-1}, the electron velocity in the first Bohr orbit; n is the principal quantum number of the state in which the electron is captured. In evaluating the cross section we summed over $n > 1$. Comparisons with experimental charge exchange cross sections (Heckman, Hubbard and Simon 1963; Nikolaev 1965; Macdonald and Martin 1971) indicate generally good agreement for $v \geqslant Z_{med} v_o$. In the region $\sim$ 13 MeV/nucleon this condition is satisfied for all abundant interstellar species. In Table 1 we list cross sections calculated for various target elements. We also list the expected contribution to the total effective cross section per interstellar hydrogen atom based on universal abundances (Cameron 1967). Note that half of the total effective cross section is due to O, and that only a small fraction may be attributed to light elements. This implies that charge exchange proceeds almost independently of the state of ionization of the medium up to temperatures of $\sim 10^6$°K.

The iron nuclei which produce the observed spectral feature could have reached charge equilibrium in the early stages of the expansion. At $\sim$ 13 MeV/nucleon the equilibrium populations of Fe^{+26}, Fe^{+25} and Fe^{+24} are comparable (Heckman, Hubbard and Simon 1963) and hence iron line emission will proceed essentially as described above. At lower energy (< 10 MeV/nucleon) equilibrium charge states with bound K electrons are favored and, therefore, such line emission is suppressed.

A competing process involves the radiative capture by the fast nuclei of ambient or loosely bound electrons (cf. Schnopper et al. 1972) which results in spectral features different from those we have discussed. An estimate, however, shows that the cross section for this process is more than an order of magnitude below that for charge exchange.

Table 1.

Charge Exchange Cross Sections Calculated for 13 MeV/nucleon Fe Nuclei Impinging on Interstellar Matter

Element	σ(cm^2/atom)	$\bar{\sigma}$(cm^2/hydrogen atom)
H	1.2×10^{-22}	1.2×10^{-22}
He	3.6×10^{-21}	2.9×10^{-22}
C	5.7×10^{-19}	2.9×10^{-22}
O	1.7×10^{-18}	15×10^{-22}
Ne	3.2×10^{-18}	2.9×10^{-22}
Mg	4.8×10^{-18}	1.9×10^{-22}
Si	5.8×10^{-18}	2.3×10^{-22}
Fe	1.7×10^{-18}	$.7 \times 10^{-22}$
		Total $\bar{\sigma}$ = 3×10^{-21}

The time for single electron capture by Fe nuclei may now be estimated from Table 1 as $2200/n_H$ years, where n_H is the total (neutral and ionized) interstellar hydrogen density. From our data we infer a rate of Fe line emission at the source of 1.1×10^{43} photons s^{-1}. Assuming one photon per Fe nucleus, the total number of iron nuclei is $N_{Fe} = 7 \times 10^{53}/n_H$. For cosmic-ray abundances (Shapiro and Silberberg

1970), the corresponding number of hydrogen nuclei is $N_H = 1.8 \times 10^{57}/n_H$, so the total mass in fast particles is $\sim 2\ M_\odot/n_H$, and the total energy is $\sim 4 \times 10^{52}/n_H$ ergs. If all the iron in the galaxy is similarly produced, we would require about $5 \times 10^9/n_H$ supernovae.

Protons will be primarily responsible for the cosmic ray produced ionization in the HII region. The average electron density may be written as

$$n_e \simeq \frac{N_H \times \frac{dE}{dt} \times T}{36 \times 10^{-6} V} \qquad (6)$$

where $T = 10^{10}$s, the age of Cas A, and $V = 2 \times 10^{58}\ \mathrm{cm}^3$, the volume of the HII region. The energy loss rate of a proton of energy E in neutral hydrogen is (Ramaty et al. 1971)

$$\frac{dE}{dt} \simeq 1.46 \times 10^{-12} n_H\, E^{-.3}\ \mathrm{MeV\ s^{-1}} \qquad (7)$$

Substituting (7) into (6) for E = 13 MeV we obtain $n_e \simeq 17\ \mathrm{cm}^{-3}$. This value is comparable to the r.m.s. density in the HII region. The coincidence, however, may be fortuitous because of a nonuniform density distribution. If the average density is less than 17 cm^{-3}, most of the particle energy went into heat and expansion rather than ionization. The model thus predicts that essentially all of the interstellar gas in the nebula surrounding the remnant has been ionized by energetic particles which are now heating the gas. (However, charge exchange still takes place with the almost neutral heavier atoms.) A necessary consequence of this heating is bremsstrahlung x-radiation arising from collisions of suprathermal nuclei with ambient electrons (Boldt and

Serlemitsos 1969). If we assume that a cosmic ray abundance (Shapiro and Silberberg 1970) of energetic nuclei (relative to iron) were ejected at $\geqslant$ 13 MeV/nucleon, then about 20% of the total x-ray flux at $\geqslant$ 7 keV may be accounted for by suprathermal bremsstrahlung. Accounting for the complete continuum spectrum down to $\sim$ 2 keV by this mechanism would require an order of magnitude more nuclei ejected at lower energies ($\sim$ 4-13 MeV/nucleon).

The Crab Nebula is roughly 3 times as old as Cas A so that it too should be source of broad iron lines, if the two supernovae were similar events. The Crab x-ray spectrum has been extensively studied and, in the range of interest, it shows no evidence of spectral features (Boldt et al. 1969). We note, however, that the line flux that we have inferred for Cas A would at most amount to 2% over the strong and flat Crab continuum, and should not be easily detectable. Data from Tycho obtained in the same flight are now being analyzed.

A test of our interpretation of the Cas A spectrum will be possible when more refined measurements of this source will be made. Specifically, the spectral feature must come from a spatially extended region and it should not show variability on time scales shorter than those of the supernova remnant.

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FIGURE CAPTIONS

Figure 1 - Incident x-ray spectrum from Cas A. The most accurate measure (with the exception of possible systematic errors) of the differential photon flux is between 2.3 and 3.0 keV, and is $.083 \pm .002$ photons $cm^{-2}s^{-1}keV^{-1}$.

Figure 2 - Residual flux after subtracting from the Cas A incident spectrum a power law spectrum with index 4.5 which includes interstellar absorption normalized to 1.4×10^{22} hydrogen atoms cm^{-2}.

INCIDENT X-RAY SPECTRUM FOR CAS A

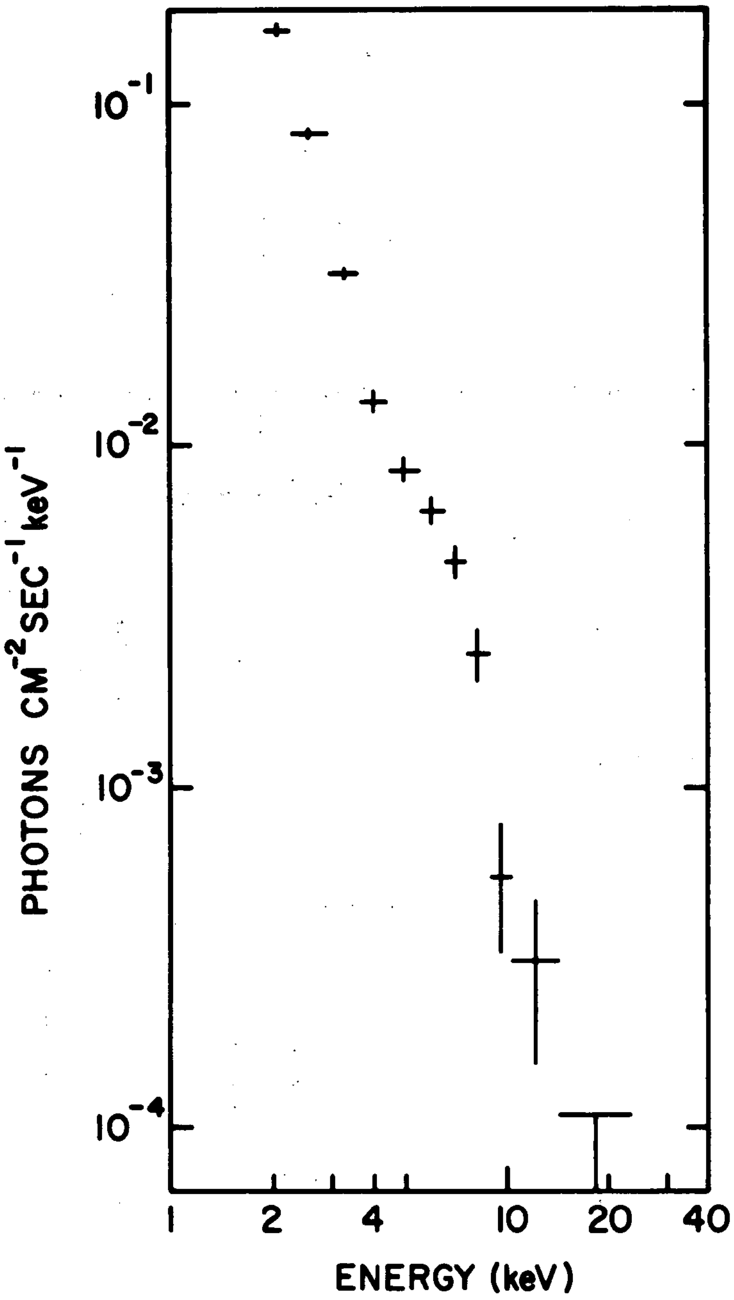

FIG. 1

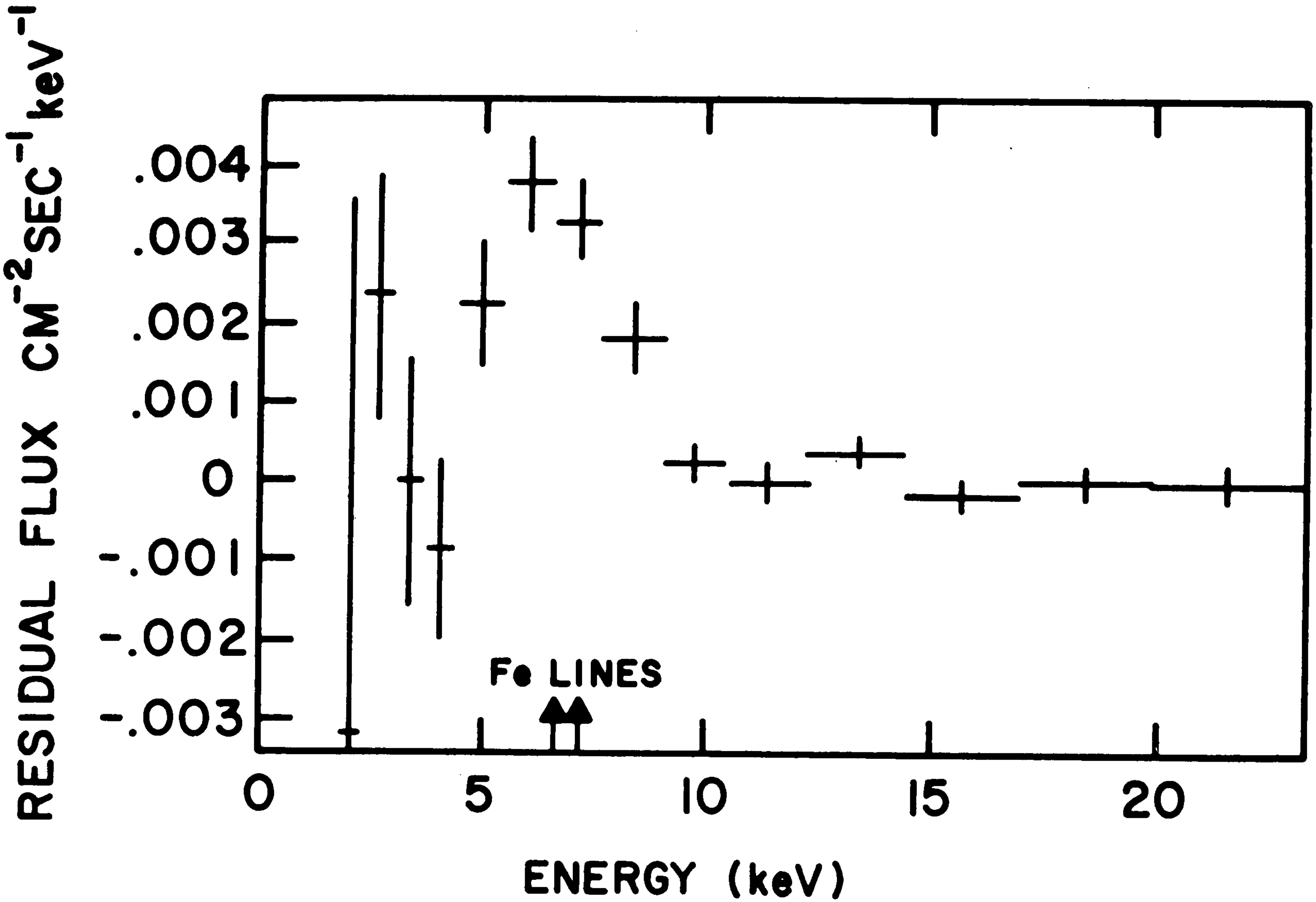

FIG. 2

NASA–GSFC